PHYSICS OF GALACTIC COLLIDERS: HIGH SPEED SATELLITES IN ΛCDM VS MONDIAN COSMOLOGY

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ABSTRACT

The statistics of high speed satellite galaxies, as reported in the recent literature, can be a powerful diagnosis of the depth of the potential well of the host halo, and hence discriminate between competing gravitational theories. Naively one expects that high speed satellites are more common in Modified Newtonian Dynamics (MOND) than in cold dark matter (CDM) since an isolated MONDian system has an infinite potential well, while CDM halos have finite potential wells. In this *Letter* we report on an initial test of this hypothesis in the context of the first generation of cosmological simulations utilizing a rigorous MONDian Poisson solver. We find that such high speed encounters are approximately a factor of four more common in MOND than in the concordance ΛCDM model of cosmic structure formation.

Subject headings: galaxy: formation – methods: N-body simulations – cosmology: theory – dark matter – large scale structure of Universe

1. INTRODUCTION

The standard ΛCDM model (cf., Komatsu et al. 2008) explains the formation of cosmological structure in the non-linear regime in a hierarchical way, i.e. large structures are not formed monolithically but by the successive merging of smaller structures (e.g,. Davis et al. 1985). Recent cosmological simulations also support the idea of hierarchical formation in MOND gravity (Llinares et al. (2008), but see also analytical models of Sanders 2008; Zhao et al. 2008). The hierarchical merging scenario naturally promotes the picture that we should observe collisions of galaxies. The question that immediately arises is what is the nature of the distribution of the relative speed of such encounters. Observationally there is evidence that some of these collisions actually occur with speeds that are not readily reproduced by simulations of ΛCDM structure formation (Hayashi & White 2006; Springel & Farrar 2007; Knebe et al. 2008). There is, for example, the famous "Bullet cluster", an extremely high velocity merger between two galaxy clusters whose relative speed is between 2500 and 4500 km/sec depending on the interpretation of the shock speed and the method used to infer the collision speed (observations/models, analytical/numerical, N-body/hydro simulations, e.g. Nusser 2008; Springel & Farrar 2007; Markevitch 2006; Zhao 2007b). At first sight, the upper limit of this interval is too high and may be a problem for the standard *Lambda*CDM model, but Hayashi & White

(2006) showed using the Millenium cosmological simulation (Springel et al. 2005) that the probability of such an event albeit low, is not zero.

There are a number of such high speed encounters in the literature. One example of such a collision is the so-called "line-of-sight Bullet", i.e. Abel 576, with a relative velocity of 3300 km/sec (Dupke et al. 2007). Furthermore the "Cosmic Train Wreck" Abel 520 is a collision with a velocity of approximately 1000 km/sec (Mahdavi et al. 2007). The "Dark Matter Ring" cluster Cl0024+17 has a speculated impact velocity of 3000 km/sec (Jee et al. 2007) and MACS J0025.4-1222 has two merging components whose relative velocity was measured to be 2000 km/sec (Bradač et al. 2008). In comparison the random dispersion of velocities in these clusters is only about 500-1000 km/sec.

A consequence of any high speed collision of mass concentrations seems to be the decoupling or offsetting of the baryons from the dark component. Assuming this being the case, additional examples of collisions are given in Jee et al. (2005a,b) but see also Heymans et al. (2008). This kind of objects, with offsets between baryon and DM components, have become what could be considered as yet another important standard test that any theory for gravity should pass before being seriously considered (e.g. Will 1993). Simply applying the MOND formula to a universe populated only with baryons seems to fail this test. Possible solutions could come from many ongoing efforts to embed the MOND idea in a relativistic framework by adding complementary (vector) fields besides the standard Einstein's metric (Bekenstein 2004; Zlosnik et al. 2007; Zhao 2007a, 2008) or by the addition of neutrinos of various kind (Angus & McGaugh 2008;

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Feix et al. 2008; Zhao 2008). However we must have in mind, that the same data on the Bullet Cluster would have rejected general relativity in its original formulation without introducing one or more dark matter components plus a cosmological constant.

The question that arises from all these data is how to match the low probability of high-speed encounters predicted by Hayashi & White (2006) for the ΛCDM model with the fact that this type of collisions *seems* to be common in the observable universe. A clue comes from the MONDian point of view where the situation seems to be more favorable for high velocities. Previous authors have noted the deep potential in MOND (Angus & McGaugh 2008; Zhao 2007b; Nusser 2008) is helpful in the context of the Bullet cluster. On a smaller scale, high-velocity stars have been studied in the context of the escape speed in the Milky Way (Perets et al. 2008). It was found that MOND can retain stars of higher velocity than CDM, and the MONDian escape velocity is more consistent with the RAVE data in the solar neighbourhood (Famaey et al. 2007; Wu et al. 2007). Further, the revised (yet still discussed) speed of the Magellanic Clouds also favors MOND (Wu et al. 2008). The question that previous authors cannot address is how to obtain a self-consistent strength of the external field in MOND since they lack a full cosmological simulation. And as MOND is a nonlinear theory it violates the strong equivalence principle and hence it is *mandatory to simulate galaxies within the cosmological framework and not in isolation.*

The aim of this paper is not to go further in an explanation of this kind of systems using MONDian ideas, but to study the consequences of a MONDian cosmological toy model on the probability of such high speed encounters. In order to do this, we study the velocity distribution of substructure extracted from cosmological simulations that have been run using standard and modified gravity. We show that high speed collisions are more frequent in MOND than in the concordance ΛCDM model.

2. SIMULATIONS

The analysis presented in this *Letter* is based upon a set of two simulations published in Llinares et al. (2008), i.e. the ΛCDM and the OCBMond2 model, respectively. Both simulations were run in a box with a side length of $32h^{-1}$Mpc, using 128^3 particles. They were both run with a modification of the N-body code `MLAPM` (Knebe et al. 2001). The ΛCDM model employs a background cosmology parametrized by $\Omega_{dm+b} = 0.3$, $\Omega_\Lambda = 0.7$, and a normalisation of the power spectrum of the density perturbation of $\sigma_8 = 0.88$. For the MONDian simulation, we chose an open universe with neither dark matter nor dark energy but characterized by $\Omega_b = 0.04$. In order to arrive at a comparable evolutionary stage to the ΛCDM model at redshift $z = 0$ we had to lower the normalisation σ_8 to 0.4 due to the faster growth of structures in MOND (cf. Sanders 2001; Knebe & Gibson 2004; Llinares et al. 2008). Both simulations were started at redshift $z = 50$ and used a Hubble constant $H_0 = 70$ km/sec/Mpc.

We used the MPI version of the `AHF` halo finder[1] `AMIGA`'s-Halo-Finder (Knollmann & Knebe 2009) to identify objects, which is based on the `MHF` halo finder of

Gill et al. (2004). For the identification of substructure we employed the tool `MergerTree` that comes with the `AHF` software package. This algorithm was originally designed to follow halos through time by tracking the membership of individual particles, but it can be also used to locate the subhalos of a given host. Since particles that belong to subhalos will belong also to the corresponding host, constructing a merger tree of a halo catalogue with itself will provide us with a "subhalo tree" (rather than a merger tree). It is important at this moment to make a remark about our terminology. We use the term subhalo to refer to the largest substructures embedded in host haloes. The mass ratio between our host halos and the most massive subhalo have a median of 0.23 and 0.15 for the MONDian and Newtonian simulations respectively. These numbers are in the range of typical mass ratios for collisions in mergers of host halos and are well above the typical ratio between hosts and real substructures (e.g. Madau et al. 2008). In order to not contaminate our result with unvirialized objects we further prune our halo catalogue by removing objects with a high virial ratio ending up with 64 and 58 objects in the Newtonian and MONDian simulations, respectively.

For more details regarding these simulations, we refer the reader to Llinares et al. (2008)

3. ANALYSIS

While the primary focus of this *Letter* is the distribution of the relative velocity of two colliding systems, we still need to define a proper normalisation for these velocities to correct for the fact that a more massive host system will lead to a larger acceleration towards its centre. While others referred to the rotational velocity at the virial radius of the host for this purpose (e.g., Hayashi & White 2006), we rather use the mass-averaged velocity dispersion.

3.1. *Velocity dispersion - Mass relation for MOND and CDM*

In the Newtonian case, the velocity dispersion scales with the mass M as follows: $\sigma \propto V_{cir} = \sqrt{GM/R} \propto R \propto M^{1/3} \propto M_{baryon}^{1/3}$, where we used $M \propto \bar\rho R^3$ where $\bar\rho$ is the background density, which depends only on redshift. A similar scaling relation between velocity dispersion σ and mass M can be easily obtained for deep MOND $\sigma \propto V_{cir} \propto (GM_{baryon}a_0)^{1/4} \propto M_{baryon}^{1/4}$ for a spherical isolated body. Although not rigorous, we find that this scaling holds fairly well as a mass-averaged total dispersion of the system even in the intermediate MOND regime.

Figure 1 shows the $\sigma - M$ relation for the host systems selected in both our simulations. The lines indicate power laws fits, whose index agrees closely with the theoretical values 1/4 and 1/3 for MONDian and Newtonian theory, respectively. The fitted normalisation is higher than the theoretical one, owning to the fact that the simulated halos break the hypothesis of constant density used in the theoretical approach.

3.2. *Normalising the relative velocities*

Special care must be taken when comparing Newtonian dark matter simulations to collisionless MONDian simulations, especially when it comes to "haloes". While we

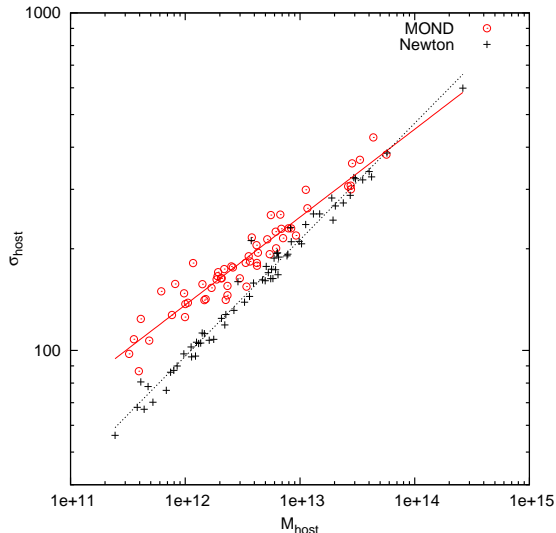---

[1] `AHF` is freely available from `http://www.aip.de/People/aknebe`

Fig. 1.— Correlations of velocity dispersion (σ_{host} in km/s) vs. effective host mass ($M_{host} = 7.25 M_{host,baryon}$ in solar masses) for virialized objects of various sizes in MONDian (circles) and Newtonian simulations (pluses). The lines are fits with arbitrary normalization for theoretically predicted scaling relations $\sigma_{host} \propto M_{host,baryon}^{1/4}$ in MOND and $\sigma_{host} \propto M_{host,baryon}^{1/3}$ in Newtonian; the best fit slopes and very close to 1/4 and 1/3 respectively. Note that the value 7.25 scales the MOND baryoninc mass to the Newtonian baryon plus halo mass.

set out to use the velocity dispersion of the host system as the normalisation of the collision velocity in order to account for the mass of the host, we have just seen that $\sigma - M$ relations scales differently in MONDian than in Newtonian physics. What we need to do now is to move both simulations into the same theoretical framework (e.g., CDM) by applying the same technique outlined in Llinares et al. (2008), i.e. we divide the MONDian (host) masses by the baryon fraction ($\frac{\Omega_{dm+b}}{\Omega_b} = \frac{0.3}{0.04} = 7.25$) to mock dark matter haloes for direct comparison to the ΛCDM model. From these "MONDian dark matter halo plus baryon masses" we apply the Newtonian $\sigma - M$ relation to obtain the appropriate σ value to compute the normalized V_{rel}/σ. Note that we actually could reverse this procedure and transform the Newtonian dark matter haloes into the MONDian frame and use the MONDian $\sigma - M$ relation to obtain the normalized velocity. We have applied both methods to our data and the results are consistent with each other. Hence we show the results only for the former method to facilitate direct comparison to other CDM simulations.

4. RESULTS

Having identified each subhalo and its corresponding host (cf. Section 2), we calculate the cumulative probability distribution of the relative velocity between host and its most massive subhalo V_{rel}. The result is shown in figure 2. We can see that the two theories have strikingly different behaviours. Both allow high speed satellites but there is a stronger tail towards high-speed in the MONDian case. The shaded lines show the high speed region, where the MONDian probability is about four times the Newtonian.

The normalisation of the relative speed was chosen in order to eliminate the increased acceleration towards more massive host systems. The credibility of the ap-
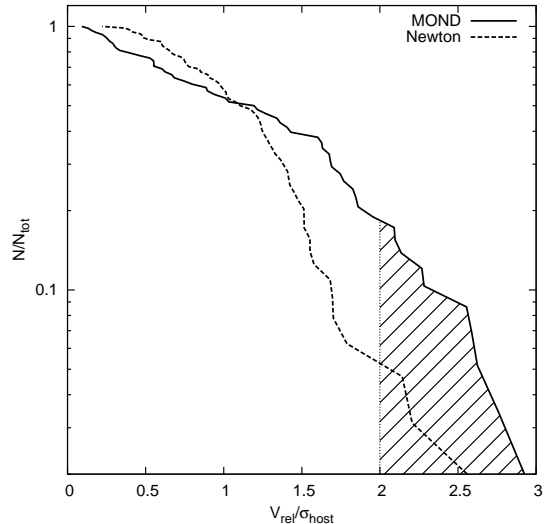

Fig. 2.— Accumulated probability of the relative velocity V_{rel} between our host halos and their most massive subhalo normalized with the effective dispersion $\sigma_{host} = 0.01(7.25 M_{host,baryon})^{1/3}$ km/sec (see text for explanation).

proach detailed in Section 3.2 can now be verified by simply dividing our sample into different mass bins. We confirm that this does not lead to different results even though we decided to not show them in this *Letter*; we basically recover the same curves as seen in figure 2.

Further, our results appear to be robust against slight changes in redshift, i.e. we neither observe a change in the fact that MONDian velocities are bigger nor are our results contaminated by the fact that we may capture collisions at a particular time of accidentally high velocity. The latter is confirmed by analysing the simulations at $z = 0.036$ leading to an indistinguishable plot. The same conclusion is reached when we experiment with other plausible normalizations or compute the distributions of un-normalised relative speed.

As a final test we compare our results against a Newtonian model that does not contain a cosmological constant Λ, i.e. the open OCBM model of Knebe & Gibson (2004) characterized by $\Omega_m = 0.04$ and $\Omega_\Lambda = 0.0$. We acknowledge (though not explicitly shown here) that the relative velocity distribution of the OCBM model is akin to the ΛCDM model presented in figure 2; we therefore ascribe the differences found in that plot to the effects of MOND rather than the (missing) cosmological constant.

5. CONCLUSIONS

Inspired by the observational evidence for high-speed encounters of galaxy clusters we studied the velocity distribution of collisions present in two cosmological simulations, a standard ΛCDM model as well as MOND. While there may be a problem for ΛCDM to accomodate such extraordinary events (e.g., Hayashi & White 2006) we set out to quantify the probabilty for them in MOND. Within the limitations of our simulations, we find that there are substantial differences in the collision velocity of objects in the standard model of cosmology and its (possible) MONDian counterpart. We observe a much greater likelihood for high-speed collisions in MOND and therefore argue that this statistic can be used as a discriminator for the two competing theories.

We further verify numerically the velocity dispersion-mass relation for deep MOND gravity whose slope is different to the Newtonian case ($\sigma \propto M^{1/4}$ for MOND instead of $\sigma \propto M^{1/3}$ for Newtonian physics). There is a mild scatter about these relations.

We close with a cautionary note: the box size of our simulation ($32h^{-1}\mathrm{Mpc}$) is too small to find objects *directly* comparable to systems like the Bullet cluster. The collisional velocity expected for the Bullet cluster ($V_{rel}/\sigma \approx 2.04$) is close to the limit of what we resolve in figure 2. While the current result is interesting, and the rescaled V_{rel}/σ is likely insensitive to details of the simulation setup, more simulations (e.g., with a possible neutrino component and a cosmological constant in MOND) are required to understand how our prediction depends on the cosmological model employed.

Nevertheless, our results here may have far-reaching implications as well. Historically, Dark Matter and MOND are competing theories. Recent studies argue that MOND is a prescription for interactions of a coupled Dark Energy-Dark Matter field. Effectively MOND is made by a non-uniform Dark Energy field. The places where this field condenses are identified as dark halos. Our results here could argue that we might differentiate between theories with interacting Dark Matter-Dark Energy vs. classical ΛCDM using data of high speed encounters. It is encouraging that some subtle differences on how the Dark Sector self-interacts could leave signatures on "large astronomical colliders" (LAC).

REFERENCES

Angus, G. W., & McGaugh, S. S. 2008, MNRAS, 383, 417

Bekenstein, J. D. 2004, Phys. Rev. D, 70, 083509

Bradač, M., Allen, S. W., Treu, T., Ebeling, H., Massey, R., Morris, R. G., von der Linden, A., & Applegate, D. 2008, ApJ, 687, 959

Davis, M., Efstathiou, G., Frenk, C. S., & White, S. D. M. 1985, ApJ, 292, 371

Dupke, R. A., Mirabal, N., Bregman, J. N., & Evrard, A. E. 2007, ApJ, 668, 781

Famaey, B., Bruneton, J.-P., & Zhao, H. 2007, MNRAS, 377, L79

Feix, M., Fedeli, C., & Bartelmann, M. 2008, A&A, 480, 313

Gill, S. P. D., Knebe, A., & Gibson, B. K. 2004, MNRAS, 351, 399

Hayashi, E., & White, S. D. M. 2006, MNRAS, 370, L38

Heymans, C., Gray, M. E., Peng, C. Y., van Waerbeke, L., Bell, E. F., Wolf, C., Bacon, D., Balogh, M., Barazza, F. D., Barden, M., Böhm, A., Caldwell, J. A. R., Häußler, B., Jahnke, K., Jogee, S., van Kampen, E., Lane, K., McIntosh, D. H., Meisenheimer, K., Mellier, Y., Sánchez, S. F., Taylor, A. N., Wisotzki, L., & Zheng, X. 2008, MNRAS, 385, 1431

Jee, M. J., Ford, H. C., Illingworth, G. D., White, R. L., Broadhurst, T. J., Coe, D. A., Meurer, G. R., van der Wel, A., Benítez, N., Blakeslee, J. P., Bouwens, R. J., Bradley, L. D., Demarco, R., Homeier, N. L., Martel, A. R., & Mei, S. 2007, ApJ, 661, 728

Jee, M. J., White, R. L., Benítez, N., Ford, H. C., Blakeslee, J. P., Rosati, P., Demarco, R., & Illingworth, G. D. 2005a, ApJ, 618, 46

Jee, M. J., White, R. L., Ford, H. C., Blakeslee, J. P., Illingworth, G. D., Coe, D. A., & Tran, K.-V. H. 2005b, ApJ, 634, 813

Knebe, A., Arnold, B., Power, C., & Gibson, B. K. 2008, MNRAS, 386, 1029

Knebe, A., & Gibson, B. K. 2004, MNRAS, 347, 1055

Knebe, A., Green, A., & Binney, J. 2001, MNRAS, 325, 845

Knollmann, S., & Knebe, A. 2009, ApJS, submitted

Komatsu, E., Dunkley, J., Nolta, M. R., Bennett, C. L., Gold, B., Hinshaw, G., Jarosik, N., Larson, D., Limon, M., Page, L., Spergel, D. N., Halpern, M., Hill, R. S., Kogut, A., Meyer, S. S., Tucker, G. S., Weiland, J. L., Wollack, E., & Wright, E. L. 2008, ArXiv e-prints

Llinares, C., Knebe, A., & Zhao, H. 2008, ArXiv e-prints

Madau, P., Diemand, J., Kuhlen, M. 2008, ArXiv e-prints 0802.2265

Mahdavi, A., Hoekstra, H., Babul, A., Balam, D. D., & Capak, P. L. 2007, , 668, 806

Markevitch, M. 2006, in ESA Special Publication, Vol. 604, The X-ray Universe 2005, ed. A. Wilson, 723–+

Nusser, A. 2008, MNRAS, 384, 343

Perets, H. B., Wu, X., Zhao, H., Famaey, B., Gentile, G., & Alexander, T. 2008, ArXiv e-prints

Sanders, R. H. 2001, ApJ, 560, 1

—. 2008, MNRAS, 386, 1588

Springel, V., & Farrar, G. R. 2007, MNRAS, 380, 911

Springel, V., White, S. D. M., Jenkins, A., Frenk, C. S., Yoshida, N., Gao, L., Navarro, J., Thacker, R., Croton, D., Helly, J., Peacock, J. A., Cole, S., Thomas, P., Couchman, H., Evrard, A., Colberg, J., & Pearce, F. 2005, Nature, 435, 629

Will, C. M. 1993, Theory and Experiment in Gravitational Physics (Theory and Experiment in Gravitational Physics, by Clifford M. Will, pp. 396. ISBN 0521439736. Cambridge, UK: Cambridge University Press, March 1993.)

Wu, X., Famaey, B., Gentile, G., Perets, H., & Zhao, H. 2008, MNRAS, 386, 2199

Wu, X., Zhao, H., Famaey, B., Gentile, G., Tiret, O., Combes, F., Angus, G. W., & Robin, A. C. 2007, ApJ, 665, L101

Zhao, H. 2007a, ApJ, 671, L1

—. 2007b, ArXiv e-prints

—. 2008, ArXiv e-prints

Zhao, H., Xu, B.-X., & Dobbs, C. 2008, ApJ, 686, 1019

Zlosnik, T. G., Ferreira, P. G., & Starkman, G. D. 2007, Phys. Rev. D, 75, 044017